Aneutronic Fusion Spacecraft Architecture

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NIAC 2012 – Spring Meeting, Pasadena, CA

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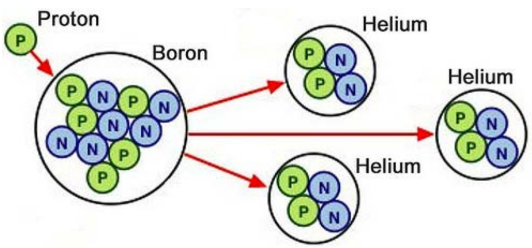
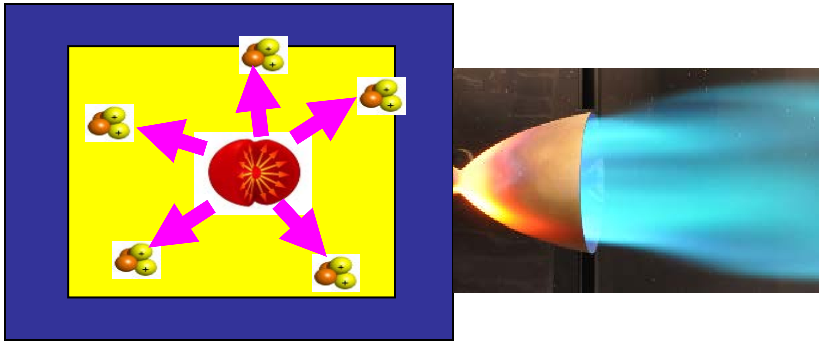
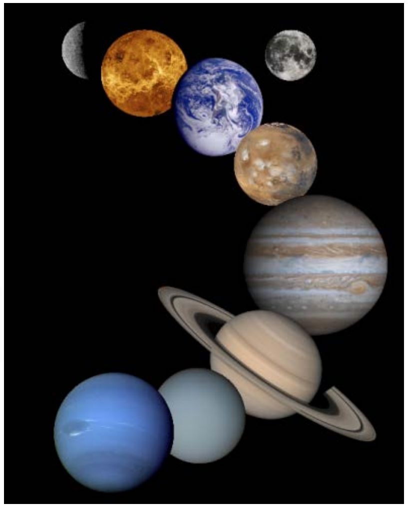
Summary



- Exploration of a new concept for space propulsion suitable for aneutronic fusion



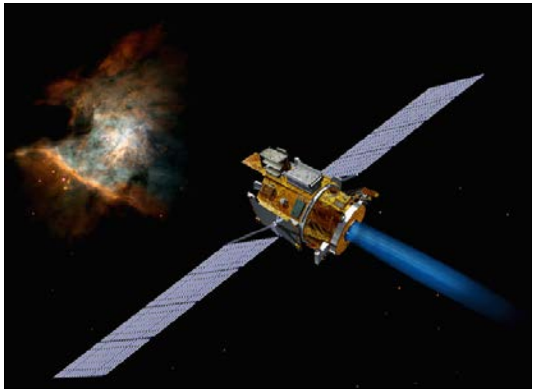
- Fusion energy-to-thrust direct conversion: turn fusion products kinetic energy into thrust

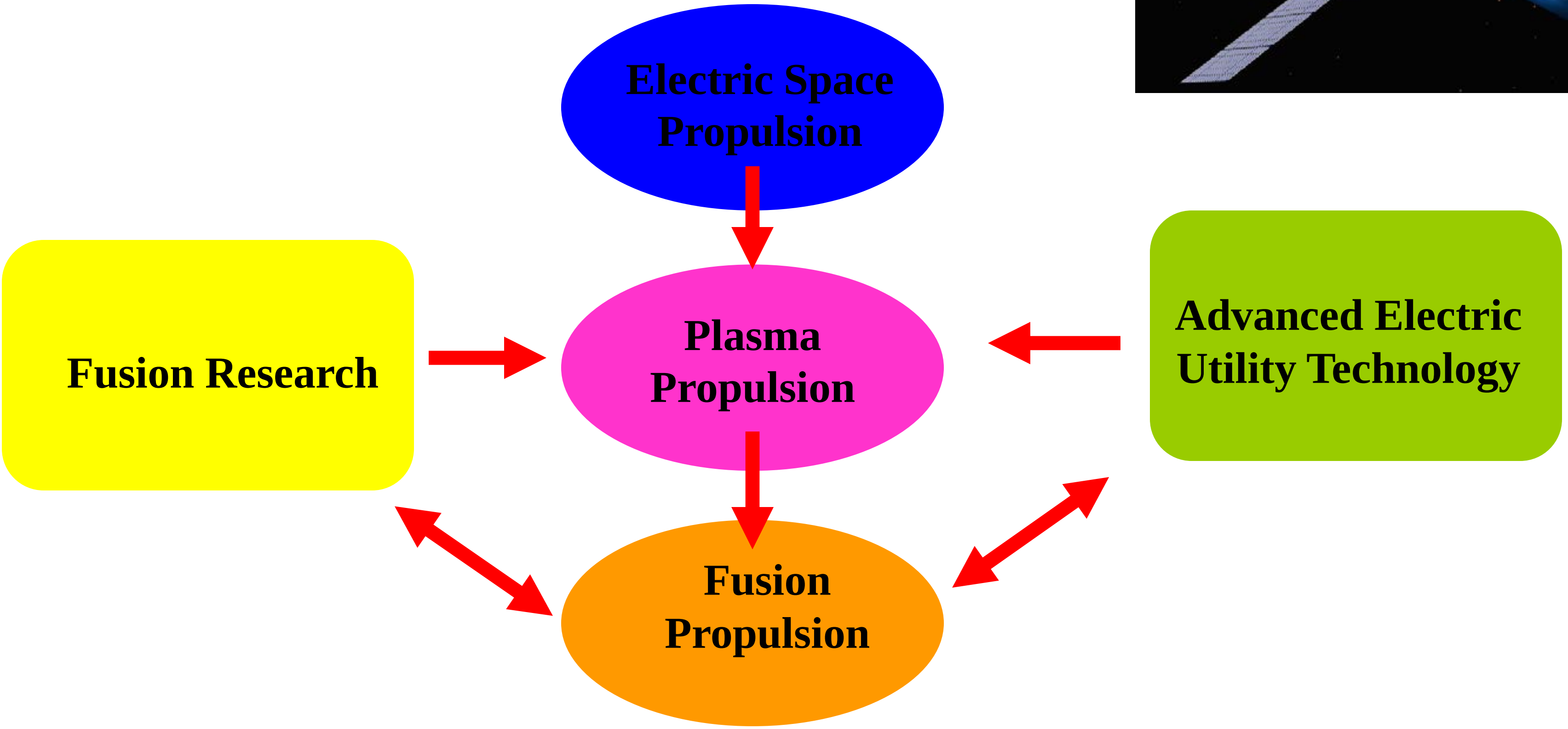


- Fusion products beam conditioning: specific impulse and thrust compatible with needs practical mission

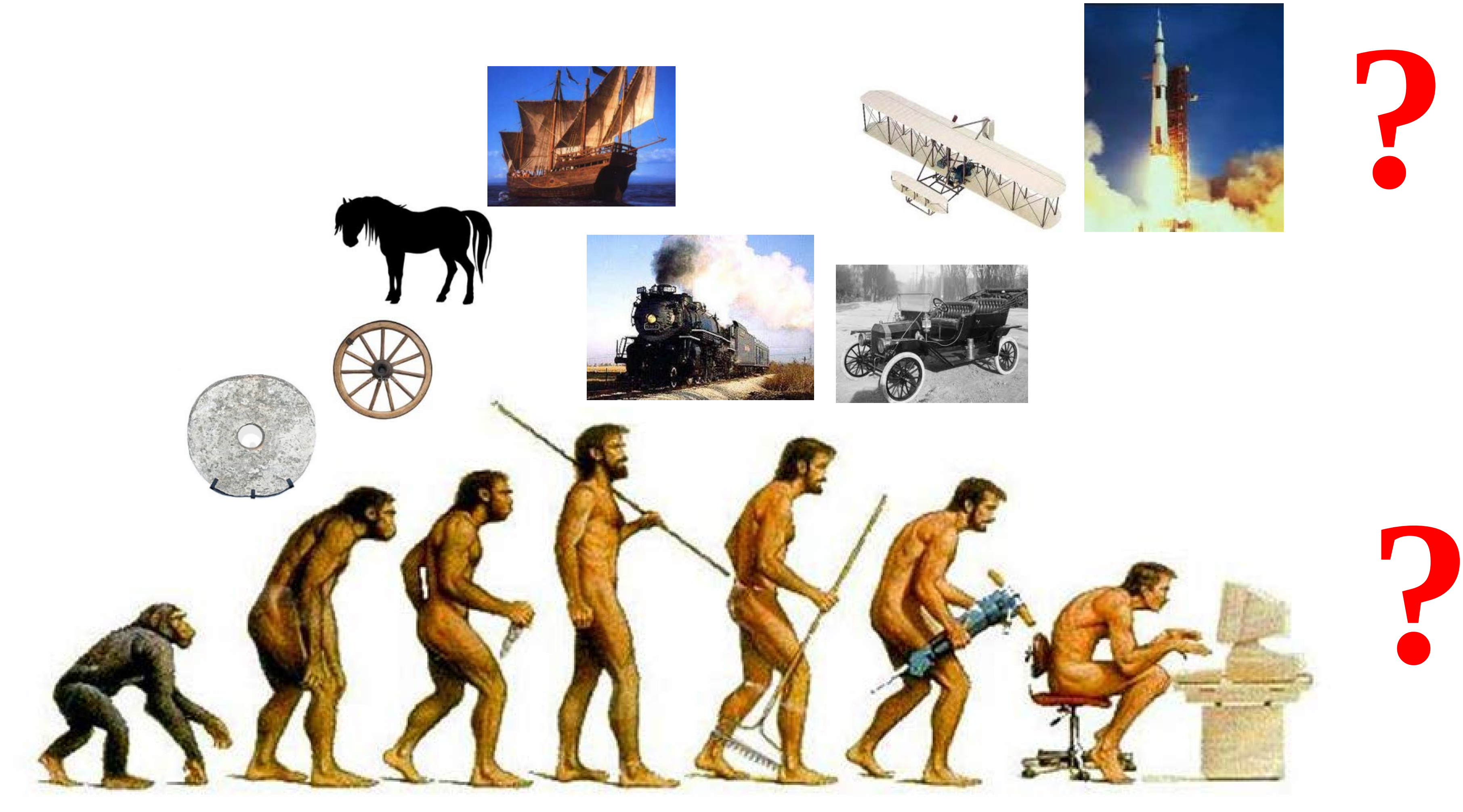
Where all this fits: the Big Picture

- "Big time" space travel needs advanced propulsion at the 100-MW level
- This really means electric propulsion
- Electric propulsion needs fusion





Introduction - Space Exploration Needs



“Game changers” in the evolution of human transportation

Introduction - Space Exploration Needs

- Incremental modifications of existing space transportation designs can only go so far…

- Aerospace needs new propulsion technologies

Introduction - Priorities

- A new propulsion paradigm that enables faster and longer distance space travel is arguably the technology development that could have the largest impact on the overall scope of the NASA mission

- In comparison, every other space technology development would probably look merely incremental

- Investing in R&D on new, advanced space propulsion architectures could have the largest impact on the overall scope of the NASA mission.

Introduction – Fusion Propulsion

- Utilization of fusion energy for spacecraft propulsion may be one of the most compelling research directions for the development of the future space program

- Fusion research has reached a high level of scientific and technological maturity through a half-century of remarkable progress

Introduction – Fusion Propulsion

- Even if a fusion reactor were to be available today, its successful application to space propulsion would be constrained by the requirements of integration with an electric thruster
- Overall system mass and efficiency is ultimately all that matters if a significant step-change in the potentials of space travel is to be achieved
- Key figure of merit: specific mass α [kg/kW]

Motivation

- Design a spacecraft architecture that, for a given payload, enables the most capable missions
- Focus on minimal overall system specific mass **α** (kg/kW)
- Choose highest energy density source (fusion is just second to matter-antimatter annihilation) and…
- …a propulsion scheme with a minimal-mass and highest-efficiency in propellant acceleration

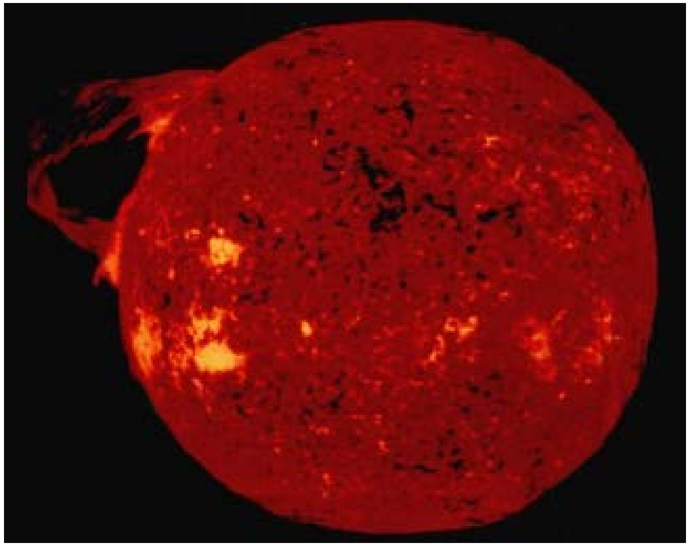
Ideal Space Propulsion

- Utilize fusion products directly for production of thrust
- The most efficient propulsion system will utilize the highest energy density source and the simplest propulsion configuration

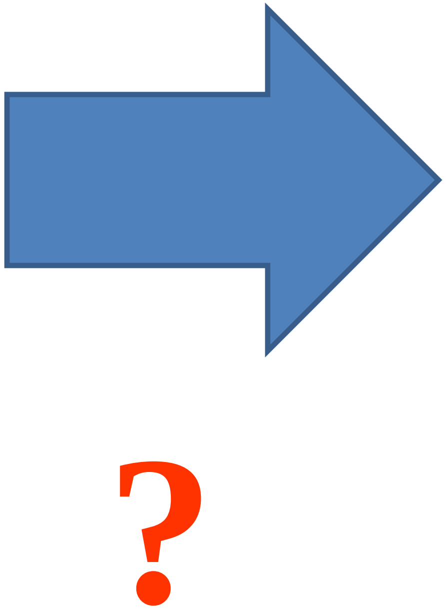
Fusion Propulsion

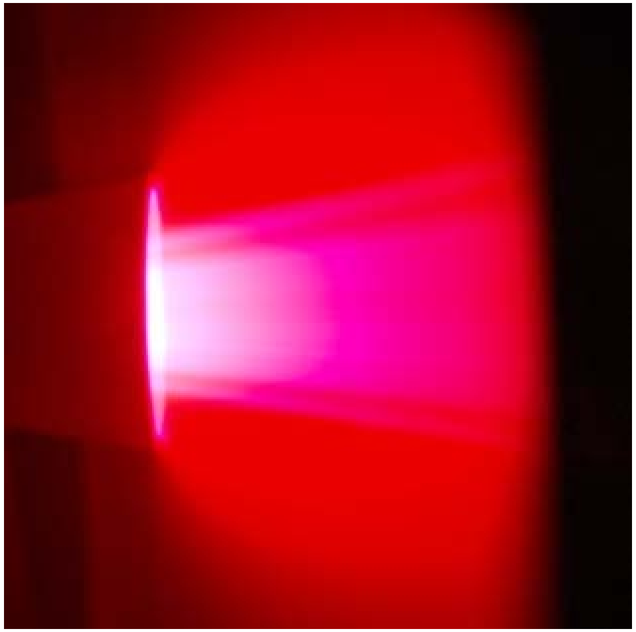
Ideal case:

Light fusion core => Fusion Products => Exhaust



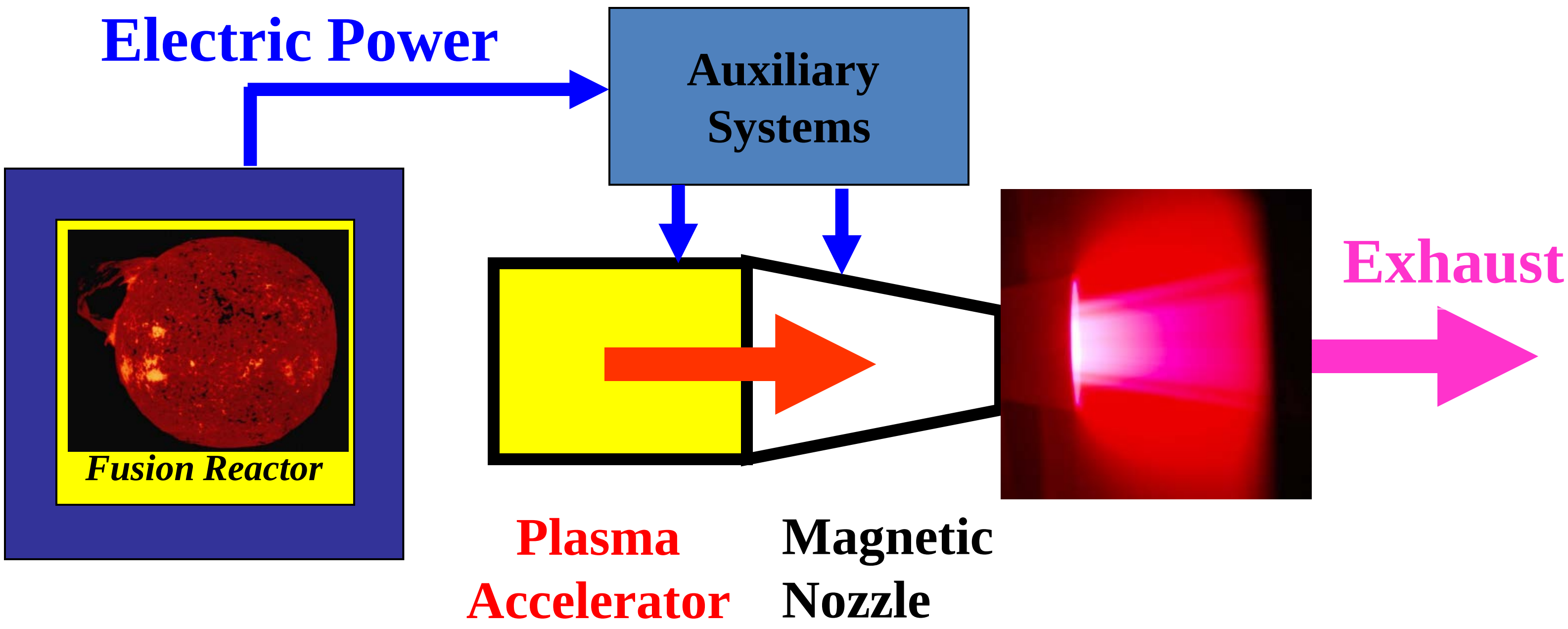
Fusion Reactor





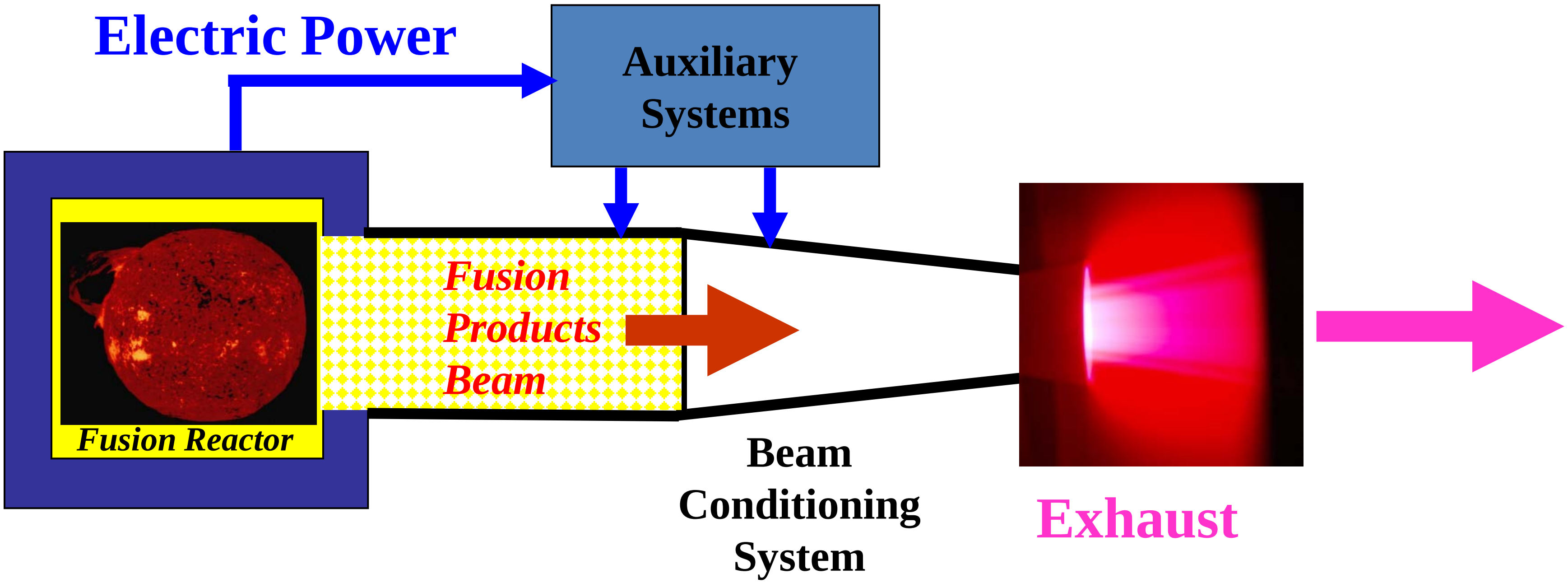
Plasma Jet Thrust

Indirect Fusion Propulsion



Electric power production and plasma generation/acceleration in an indirect fusion propulsion scheme

Direct Fusion Propulsion



Plasma exhaust production in a direct fusion propulsion scheme

Mission Design

- For a given mission and given power and initial mass, there is an optimal specific impulse profile that allows the fastest transfer
- In the gravity-free approximation, it can be shown that the optimal specific impulse (I_{sp}) is proportional to the trip time (shorter trips will require more thrust, less I_{sp}) [Moeckel, 1972]
- For "reasonable" travel in the Solar System the optimal I_{sp} is in the 10^4 s range

W. E. Moeckel, J. Spacecraft, 6 (12), 863 (1972) and NASA-TN D-6968 (1972)

Aneutronic Fusion

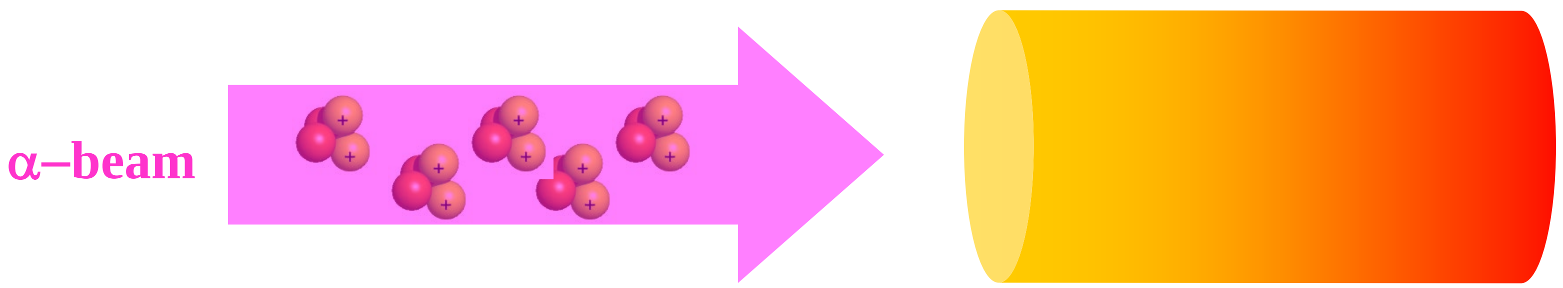
- Fusion products from main aneutronic reactions:
  - p + ^{11}B => 3 ^{4}He +8.7 MeV
  - 2.9 MeV α-particle ’ speed ≈10^7 m/s (simplification: each α-particle is considered having an energy of 2.9 MeV)
- D + ^{3}He => p (14.7 MeV) + α (3.7 MeV)
  - 3.7 MeV α-particle ’ speed ≈$1.3 \cdot 10^7$ m/s
  - 14.7 MeV proton ’ speed ≈ $5.3 \cdot 10^7$ m/s
- These reactions give a specific impulse in the 10^6 s range; too high for most practical purposes

Basic Constraints

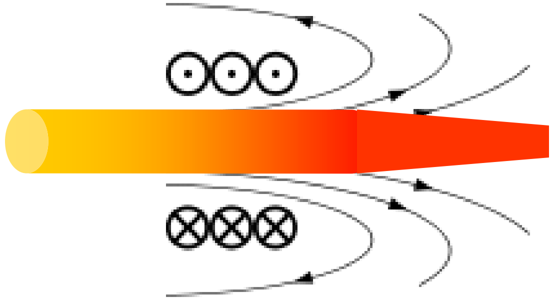
- A jet of particles (beam) with velocity v and a mass flow equal to dM/dt (kg/s)
- (Momentum) Thrust $F_{th}=v\,(dM/dt)$
- The specific impulse is conventionally expressed in seconds and defined as $I_{sp}=v/g_0$, where g_0 is the Earth gravity acceleration
- Then, for a given power, to decrease the I_{sp} and increase the thrust at the same time the mass flow needs to be increased

Old Thinking: “Slush” Plasma Propellant

- The α’s are injected into a denser, cold plasma
- After exchanging momentum and energy the propellant will be faster and warmer

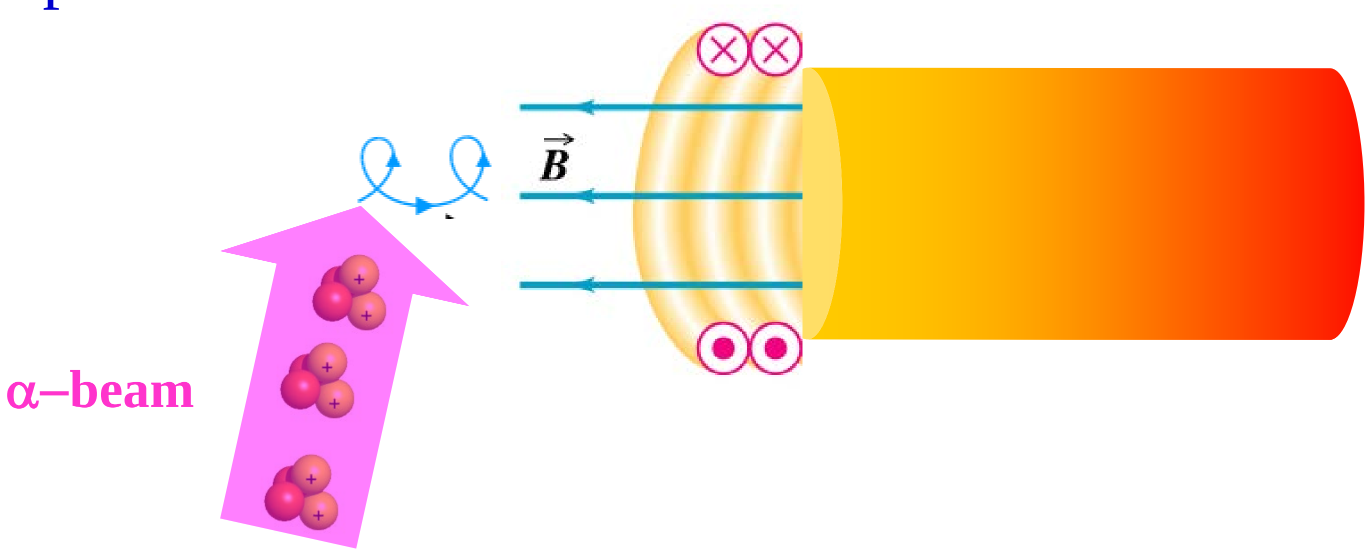


- A magnetic nozzle will redirect (most of) the thermal energy into the direction of thrust



Old Thinking: “Slush” Plasma Propellant

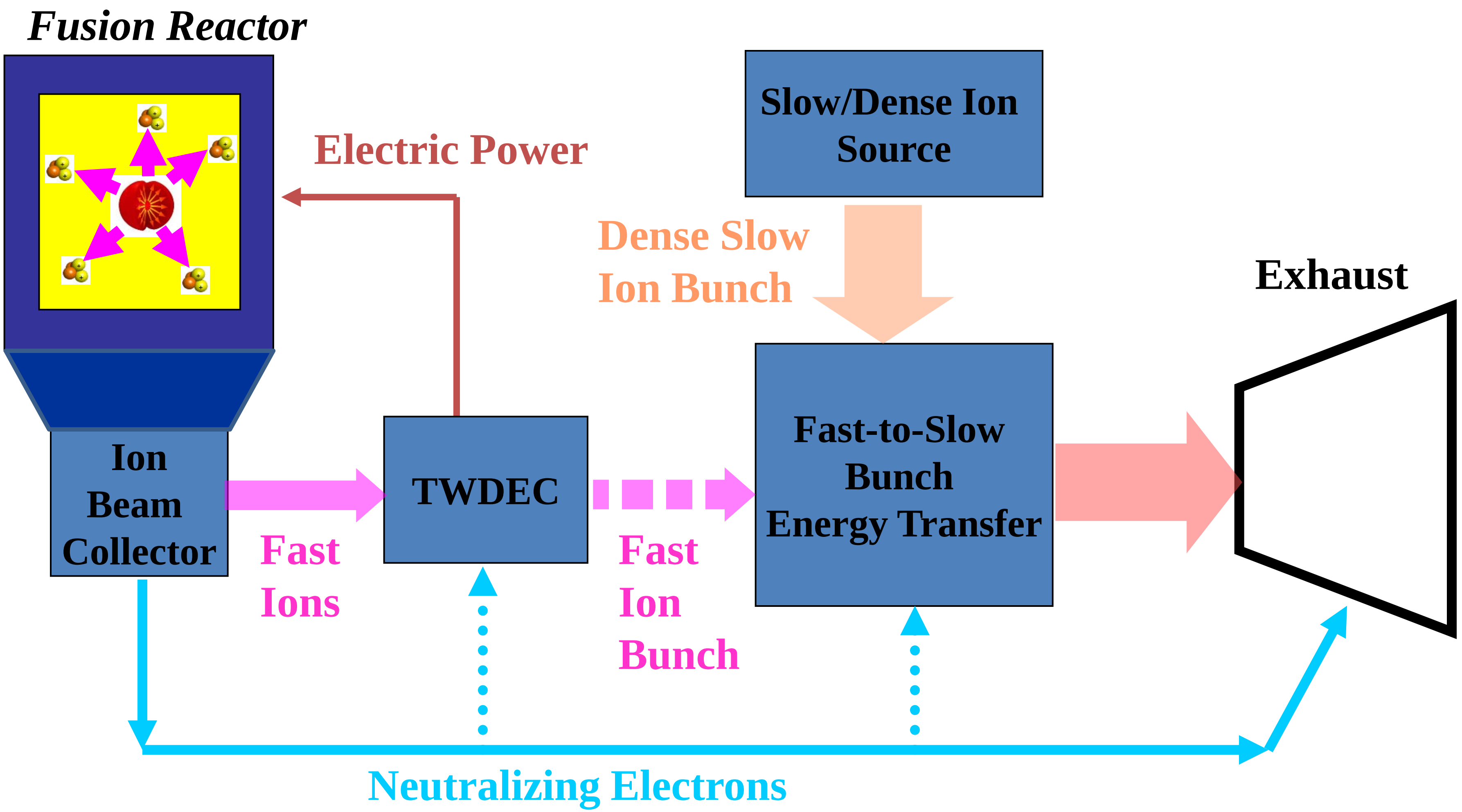
- By injecting the alpha's with a large angle w.r.t. the axis of the magnetic nozzle solenoidal field the longitudinal speed will be reduced.



- The gyro radius for a 2.9 MeV α in a 1 T field is about 0.25 m: to capture the ions the injection has to be non-adiabatic (plasma collisions)

The Proposed Approach:
Fusion Energy-to-Thrust Direct Conversion

Fusion Energy to Thrust Direct Conversion



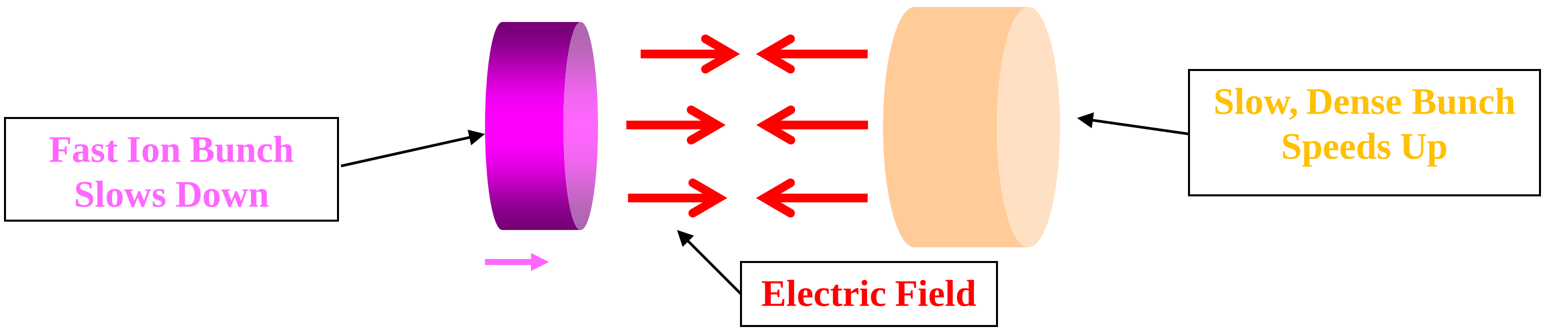
(TWDEC=Travelling Wave Direct Energy Converter)

System concept

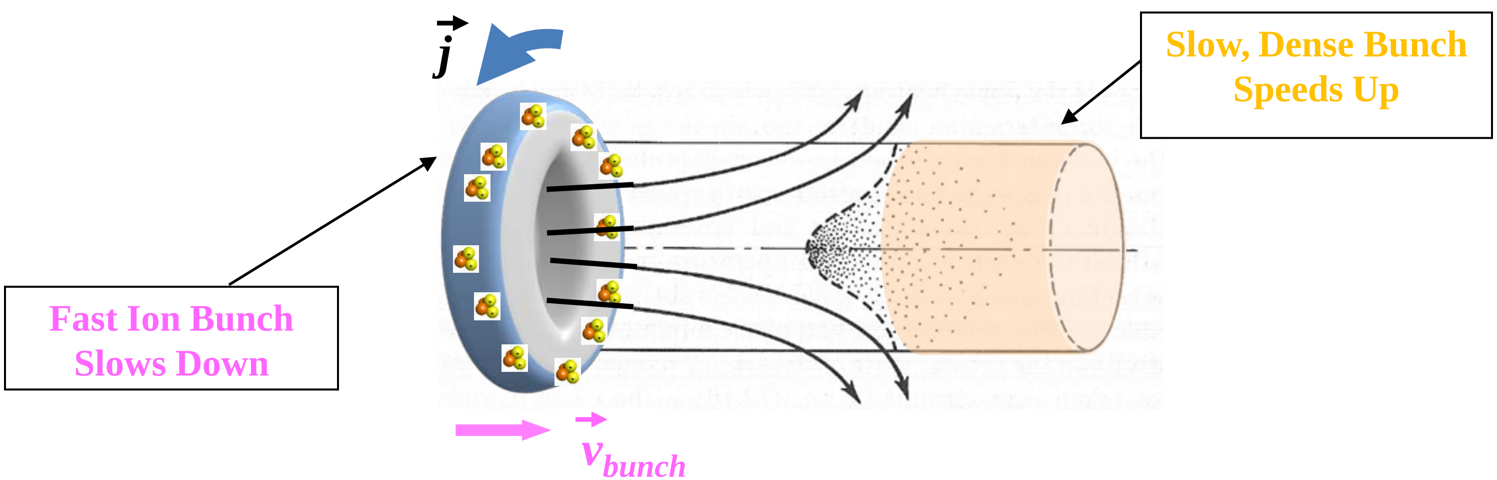
Converting Beam Energy into Thrust

Two basic processes operate concurrently:

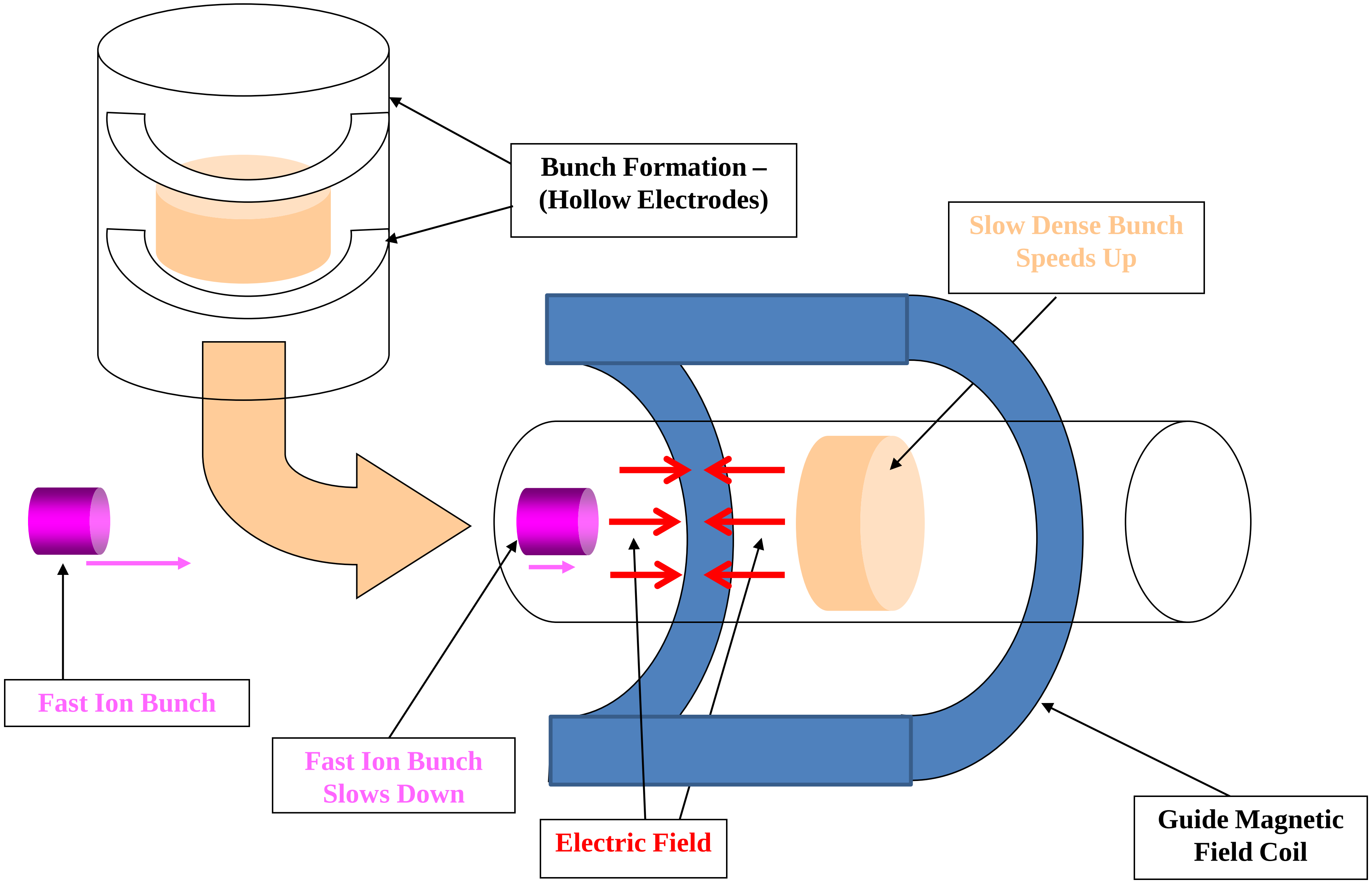
1. **Fast-to-Slow Bunch electrostatic energy exchange**



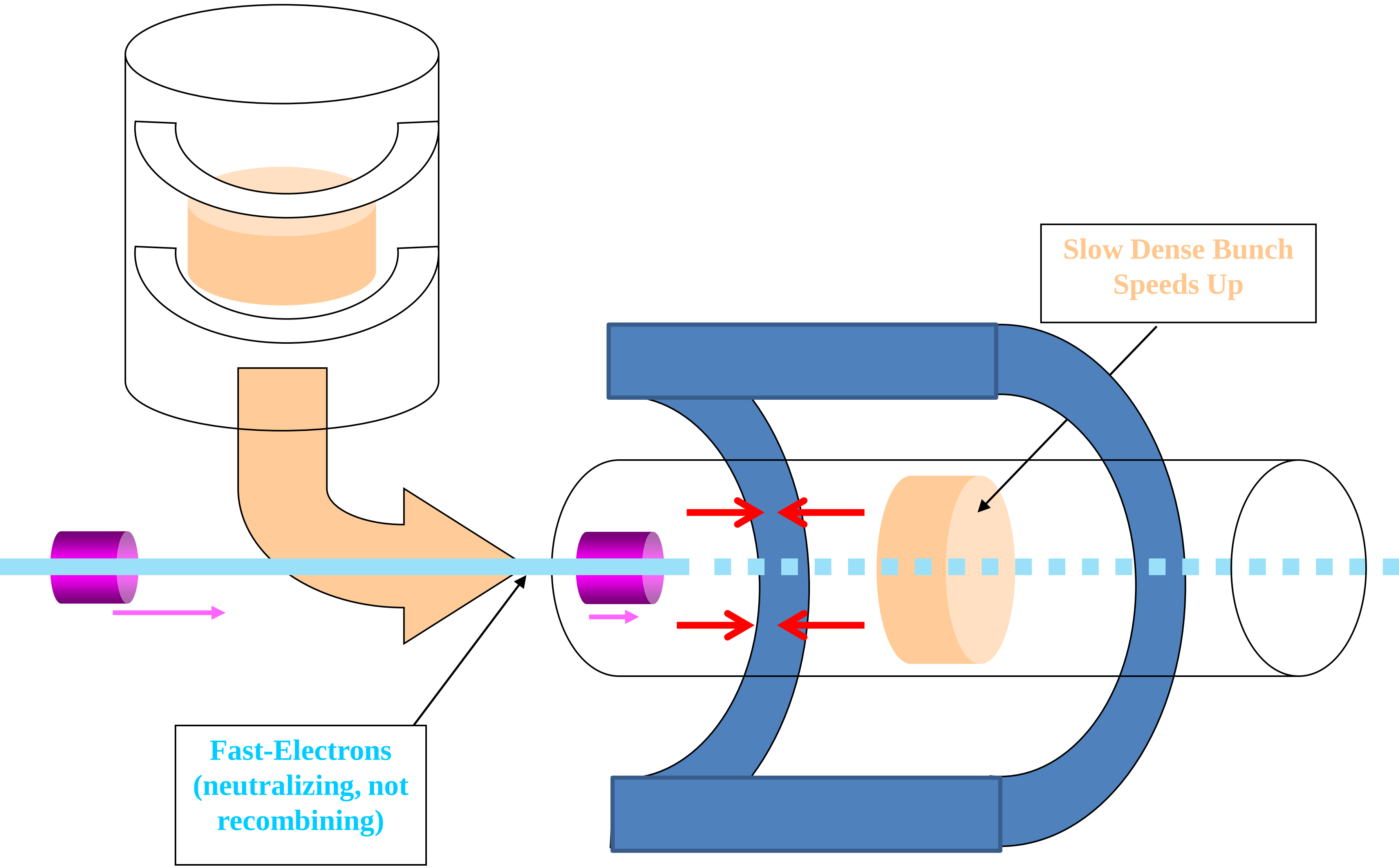
2. **Magnetic Piston effect** created by fast beam bunches confined into a spiral trajectory



1) Fast-to-Slow Bunch Energy Exchange



Fast-Electron, Neutralized Beam Scenario



Fast-electron beam (possibly partially neutralizing) may allow higher densities

“Magnetic Piston”: an Old Concept

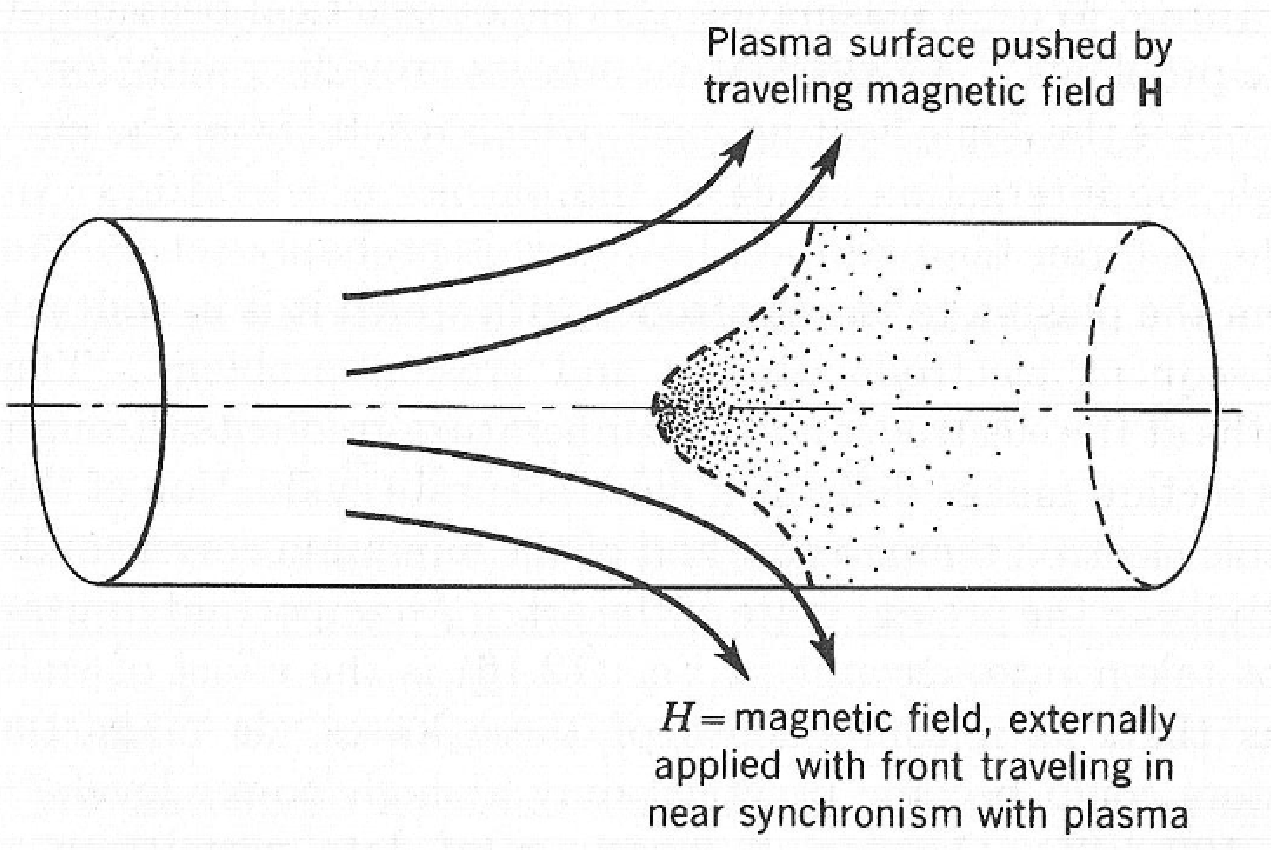
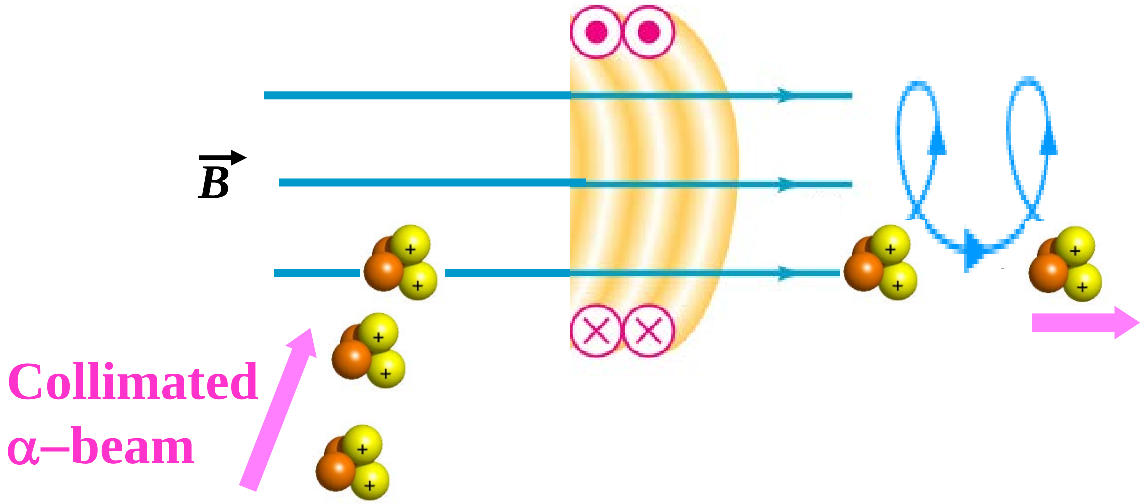


Fig. 12.23 Magnetic piston.

Concept illustration (from W.B. Kunkel, “Plasma Physics in Theory and Applications”, 1966)

Magnetic Piston: *1) Beam Injection*

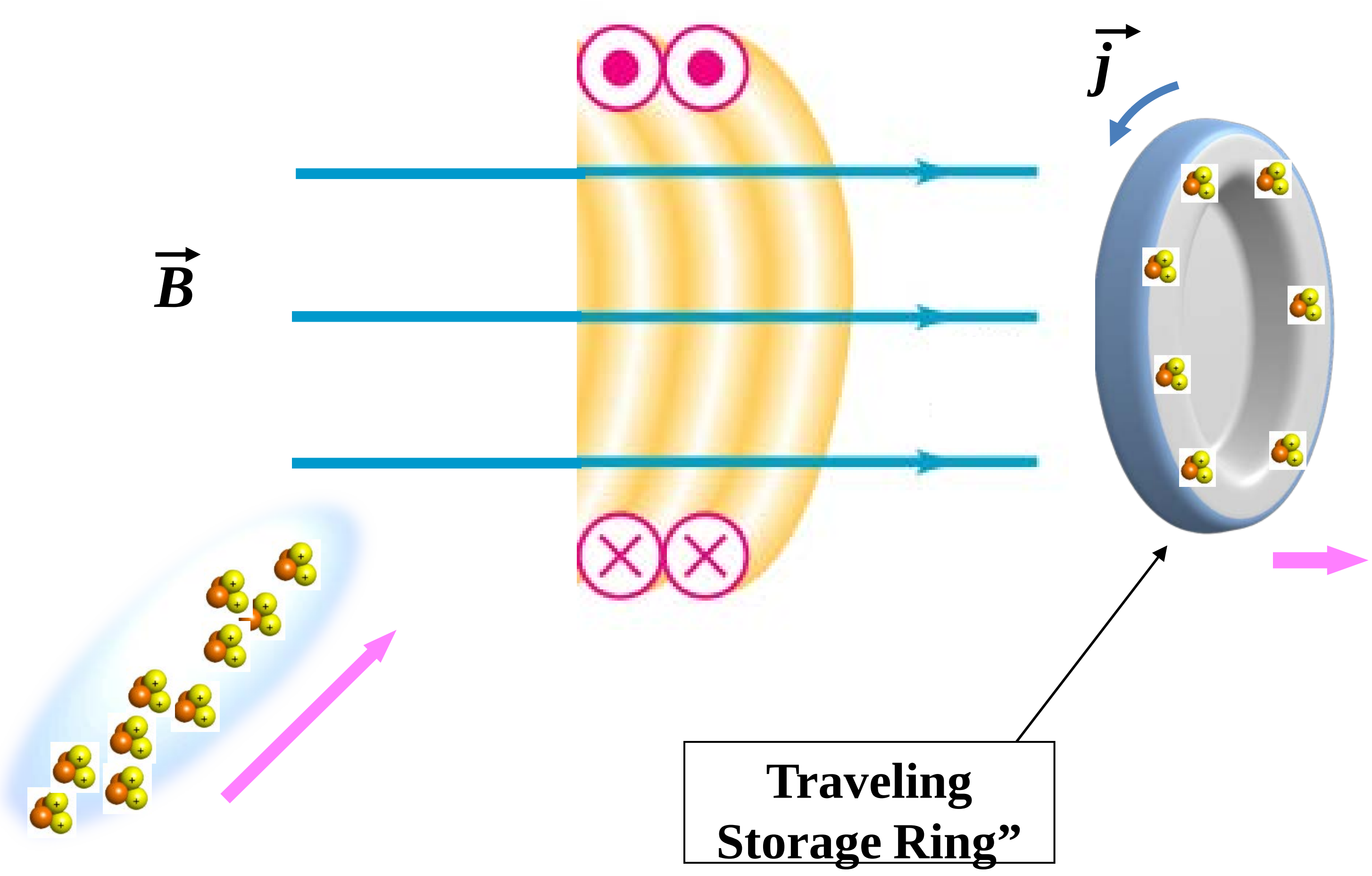
STEP 1. Injecting fusion products with a large angle w.r.t. the axis of a solenoidal magnetic field: the longitudinal speed will be reduced and particles follow a spiral orbit



- The gyro-radius for a 2.9 *MeV* α–particle in a 1 *T* field is about 0.25 *m*.
- Bunching can allow for non-adiabatic injection required to capture the ions.

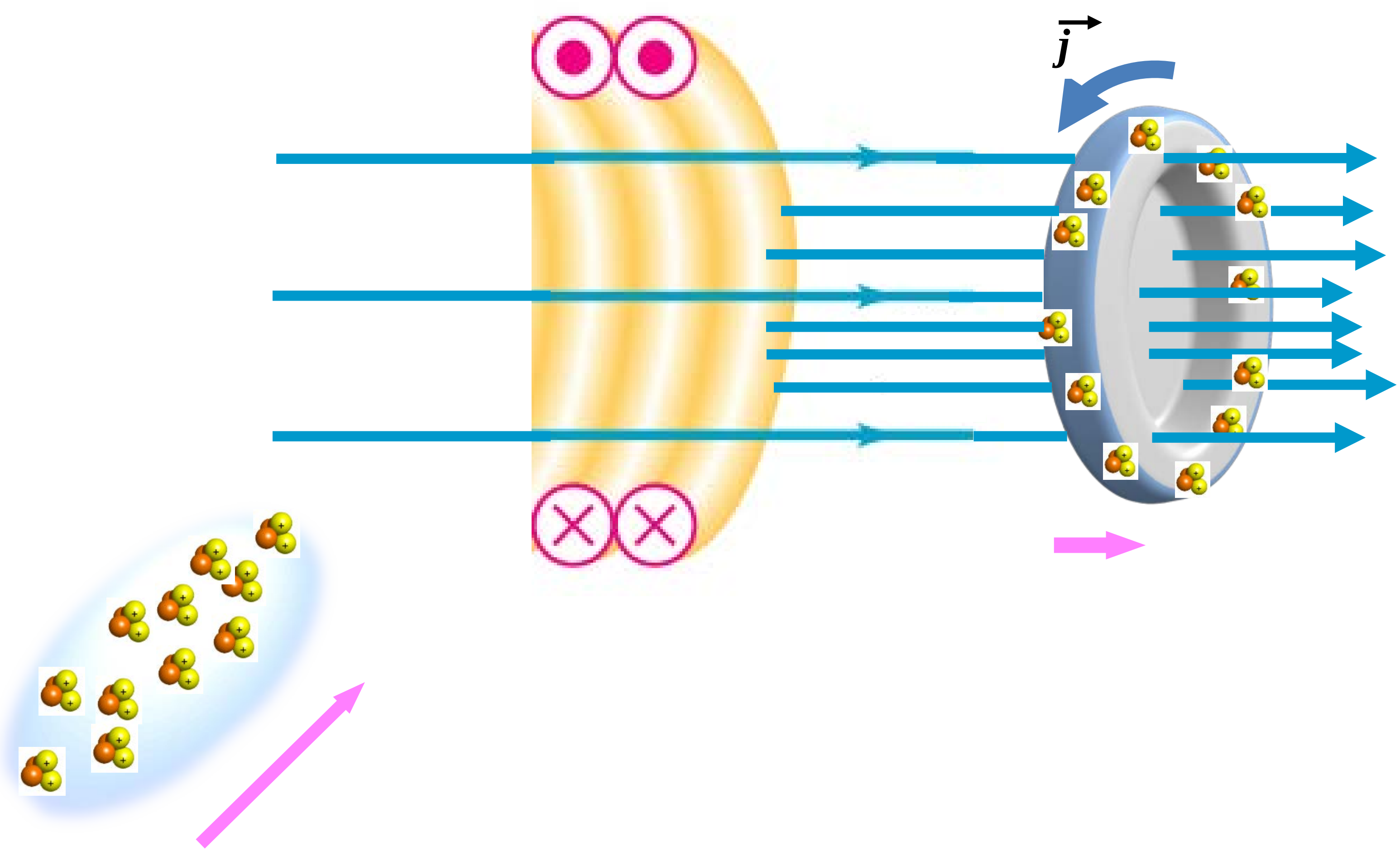
2) Formation of Current Layer

STEP 2. With a collimated, pencil-beam injection, the accumulation of ion bunches forms a current ring

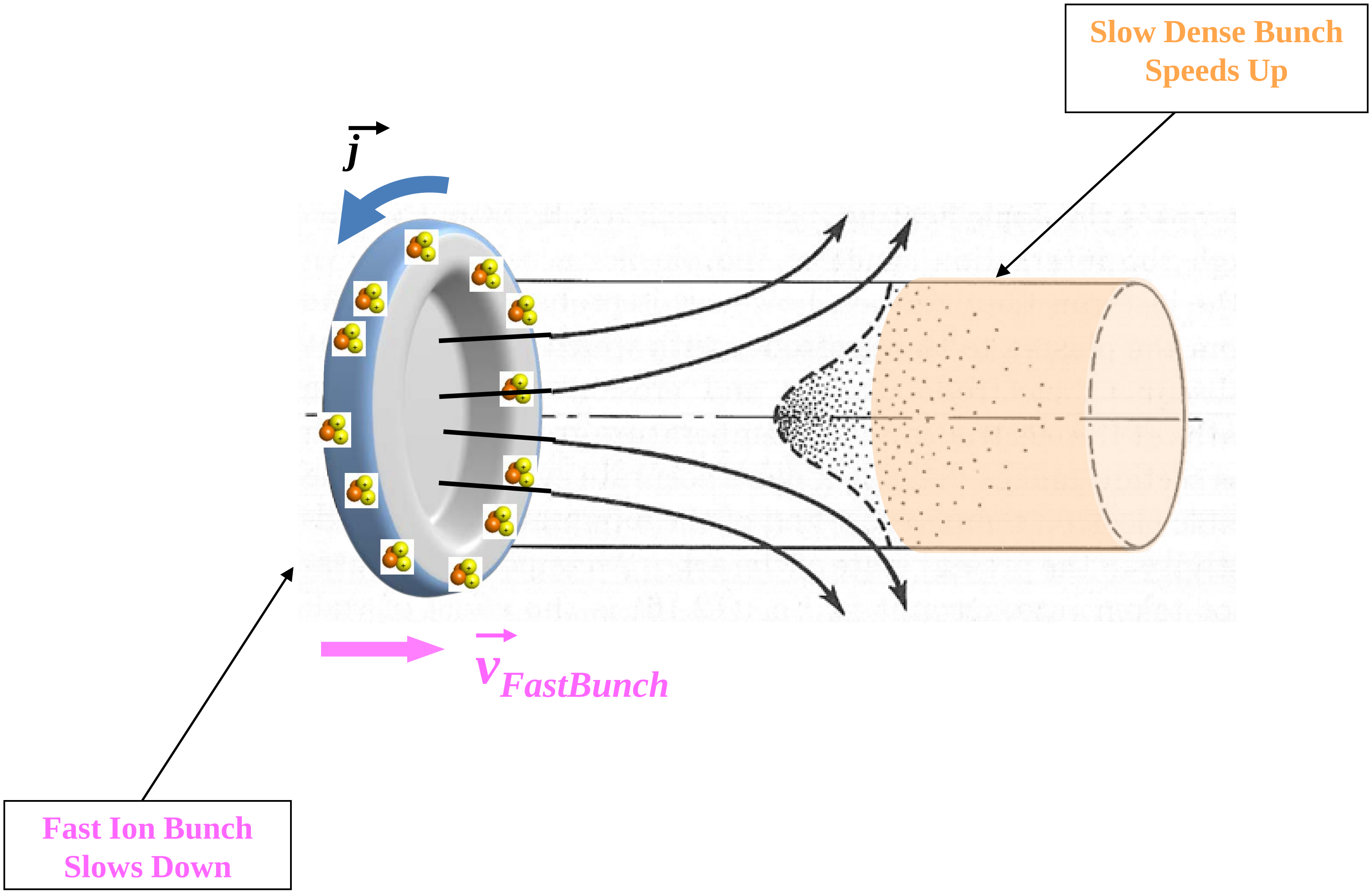


3) Magnetic Field Increase

STEP 3. As more particles are collected the current in the layer increases that, in turn, increases the magnetic field



Magnetic Piston Pushing Target Ion Bunch



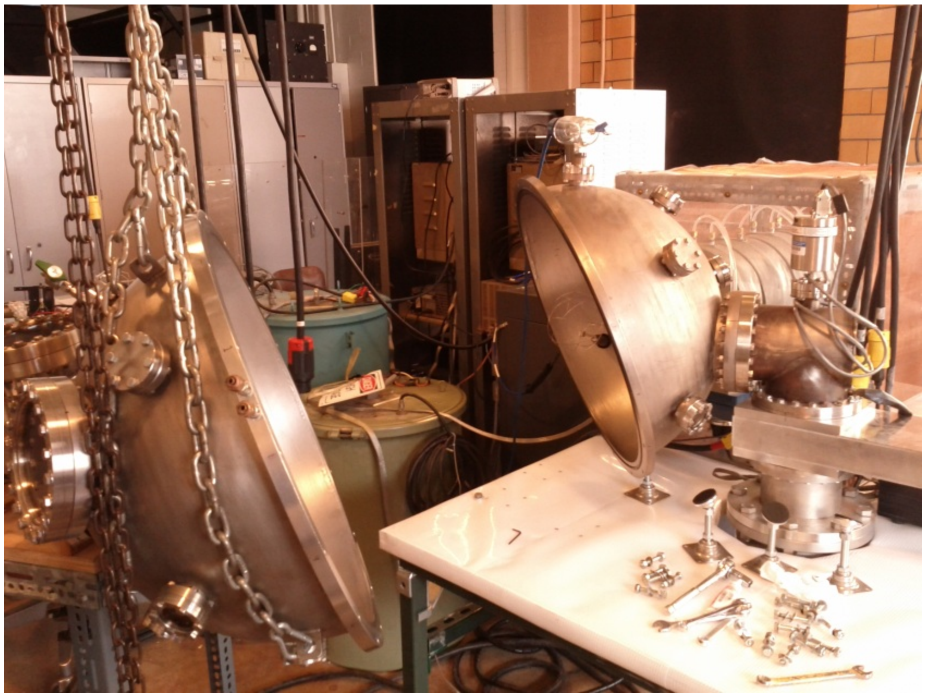
Particle-in-Cell Simulation

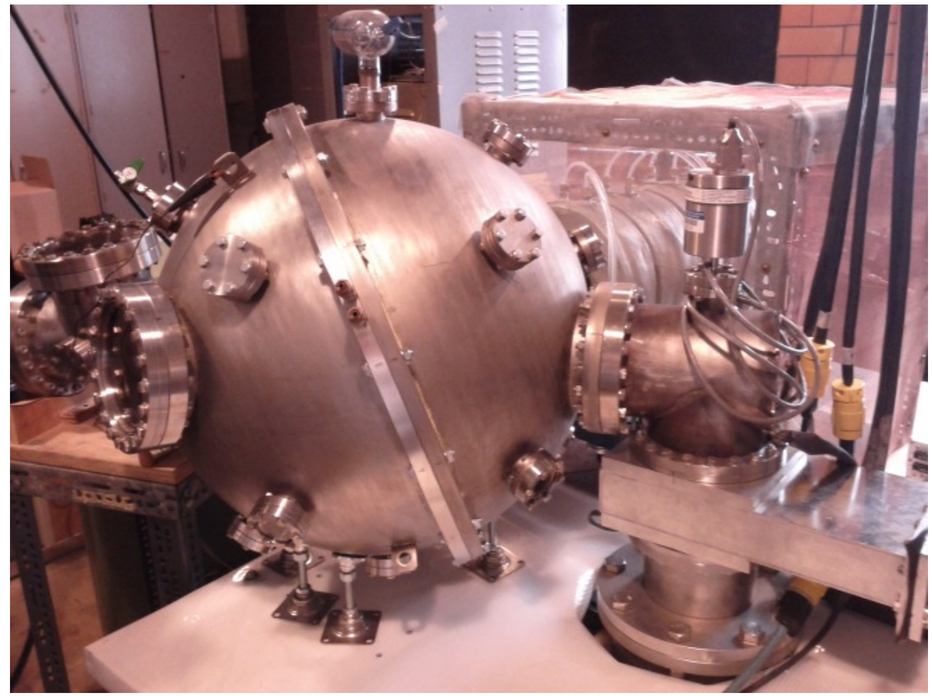
Testing α-particle bunch expansion in 0.1x1 m "can"

Near-Term Experimental Plans

- University of Illinois Urbana-Champaign (UIUC) Fusion Studies Lab: experimental campaign on key physics issues:
  - Utilization of the Helicon Injected Inertial Plasma Electrostatic Rocket (HIIPER) plasma jet for the generation of a high-density ion “bunched” beam
  - Validating the direct energy-to-thrust conversion via fast-slow bunch interaction
  - Testing of the TWDEC at higher density: TWDEC stage directly connected to a IEC plasma device.

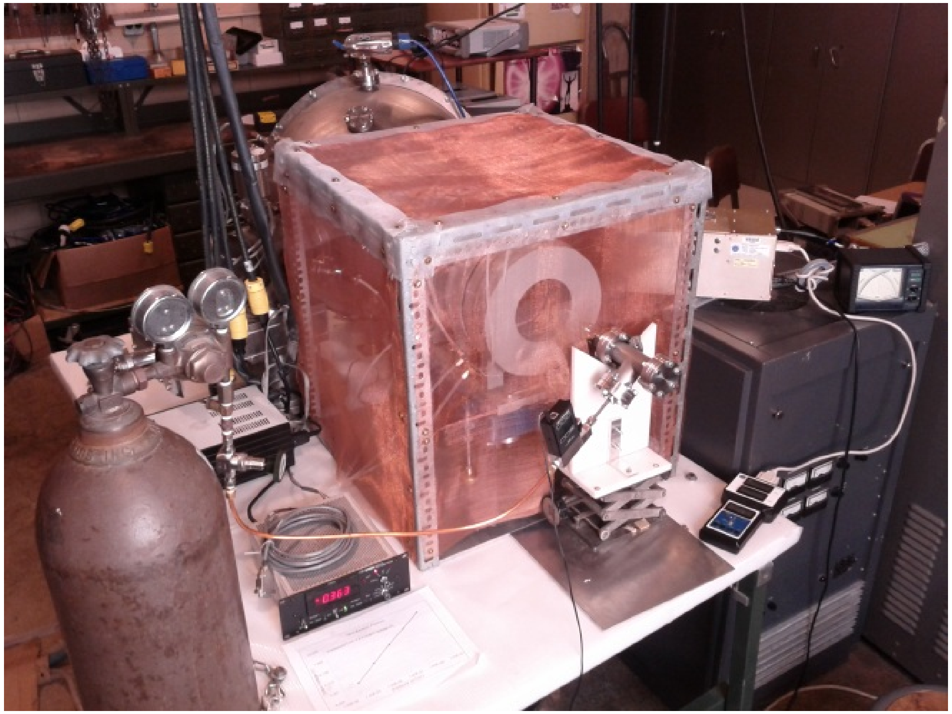
UIUC Fusion Studies Lab

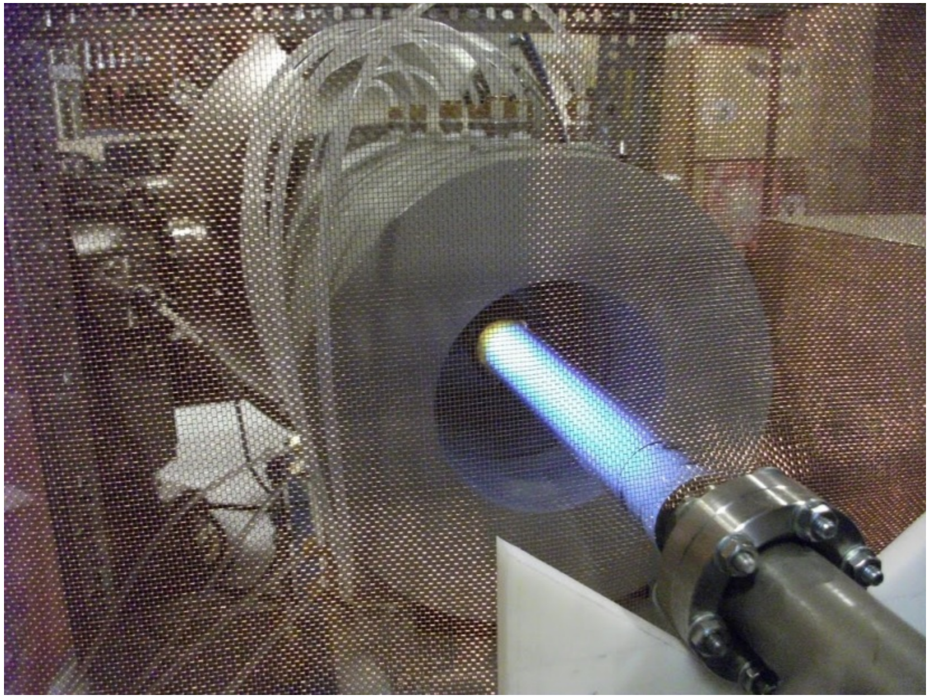




IEC Device at UIUC: 50 kV, 50 mA, 1 kW max. 44" diameter spherical stainless steel IEC chamber. Base vacuum <10^{-6} Torr

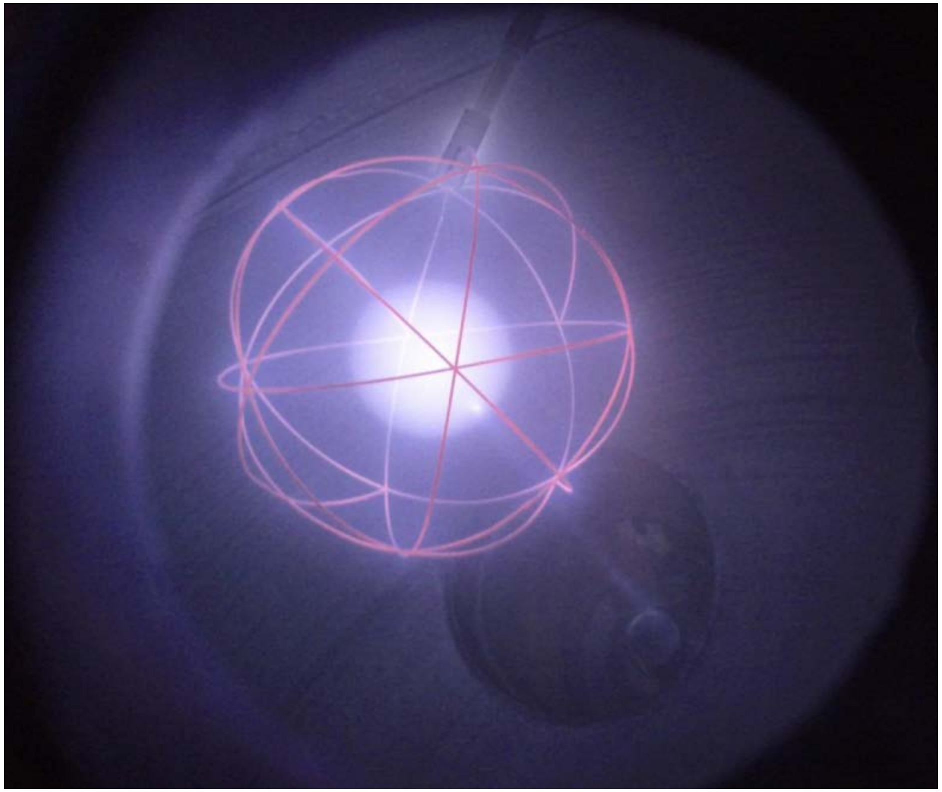
UIUC Fusion Studies Lab

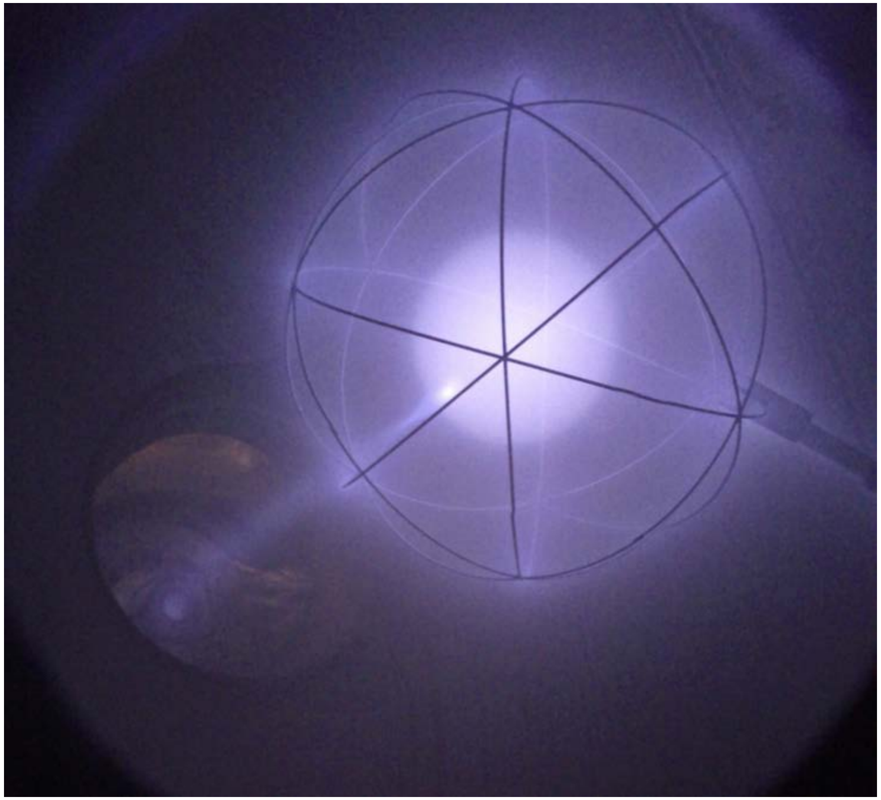




IEC Device at UIUC: plasma from a 2.2 kW Helicon source

UIUC Fusion Studies Lab





IEC Device at UIUC: IEC plasma with energized grid and formation of plasma jet

Research Plan F.Y. 2011-2012

We are here

1^{st} Quarter	*Physics process definition at the system-level and evaluation of overall performances.*
2^{nd} Quarter	*Particle-in-Cell computer modeling and simulation of subcomponents*
3^{rd} Quarter	*System-level modeling refinement, in-depth simulation and testing of overall performances and key physics issues*
4^{th} Quarter	*Revised detailed design. Final recommendation for next-step developments.*